Telecom Australia

Telecom Information Kit No. 3

THE SWITCHING PLACE

1 The first telephone exchanges

When Alexander Graham Bell invented the telephone in 1876, he at first struck many problems in convincing people of the worth of the instrument. It was called an "electrical toy" by the head of Western Union, the telegraph monopoly in the United States, who saw it as no danger to their own business. But within a few years, telephones were being used in every major city of the world, and the telegraph companies were frantically trying to get in on the telephone business.

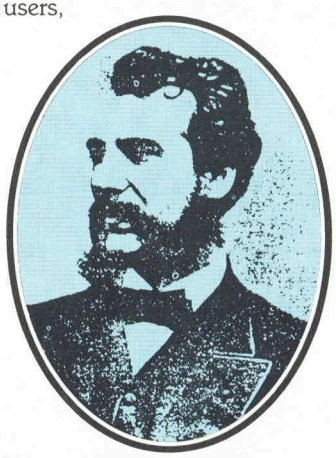
This rapid turn-around in the telephone's fortunes was almost certainly due to the organisation and setting up of the first telephone exchanges.

Bell himself had foreseen the need for exchanges in order to make the telephone business profitable. In an early letter to his supporters, he wrote:

"At the present time we have a perfect network of gas pipes and water-pipes throughout our large cities...In a similar manner, it is conceivable that cables of telephone wires could be laid underground, or suspended overhead, communicating by branch wires with private dwellings, counting houses, shops, manufactories, etc., etc., uniting them through the main cable with a central office where the wire could be connected as desired, establishing direct communication between any two places in the city...Should this plan be adopted, the company should employ a man in each central office for the purpose of connecting wires as desired. A fixed annual rental could be charged for the use of wires, or a toll could be levied. As all connections would necessarily be made at the central office, it would be easy to note the time during which any wires were connected and to make a charge accordingly–bills could be sent in periodically."

This passage was truly prophetic, and it encapsulates neatly all of the important functions of telephone exchanges right up to the present day: the exchange allows any two telephone users to speak to each other, without having a permanent direct wire between them; it allows them to be connected together and disconnected when they so desire; it supervises the progress of the call and makes a charge accordingly.

Without an exchange, every user would have to have a separate wire connected directly between his instrument and that of every other person he might wish to speak to. The number of wires in such a system would grow prodigiously. If we assume that every telephone owner in a town desires to be able to speak to every other, then a simple calculation will tell us how many wires would be needed: for five users, 10 wires would be necessary; for ten users, 45 wires; for twenty, 190; for a hundred, 4950; while for a thousand users, nearly half a million wires would be needed! As you can see, such a system would rapidly get out of hand. With an exchange system, however, only as many wires were needed as there were subscribers* to the exchange.



A. Graham Bell.

Alexander Graham Bell, the inventor of the telephone

In these early telephone systems, only a single strand of wire was taken to each subscriber's telephone: the return circuit for the electricity being through the earth. It was eventually found, however, that much better transmission of speech was possible using a "metallic circuit", where a pair of wires was provided to each telephone, allowing a return of the electricity over a metal pathway. We shall speak of the connection between a subscriber and the exchange as being one "line" regardless of how many wires were involved (for example, early automatic systems demanded up to five wires to each subscriber's line).

The first telephone exchange in the world opened at New Haven in the American State of Connecticut in January, 1878, and others followed rapidly. Australia's first telephone exchange opened in August 1880 in Melbourne followed by one in Brisbane within two months, and the following year by one in Sydney.

These first exchanges were all operated manually; that is, as Bell had suggested, men (or, more often, young women) were employed to connect the required lines together. Of course there was more to it than that. There had to be a way for a subscriber to alert the operator at the exchange that he or she wanted to make a call, and a way for the operator to alert the called subscriber that he or she was wanted. And of course there had to be a simple method for the operator to connect together any two lines coming in to the exchange. A note would also be made so that the caller could be charged for the call.

*The term "subscriber" was applied to telephone users because in the early days of telephone exchanges, people subscribed to the telephone service, rather than buying instruments outright. The terms "subscriber", "user" or even "customer" are today used interchangeably to mean the same thing. But many telecommunications terms incorporate the word "subscriber", so we will use this term most frequently in this kit.

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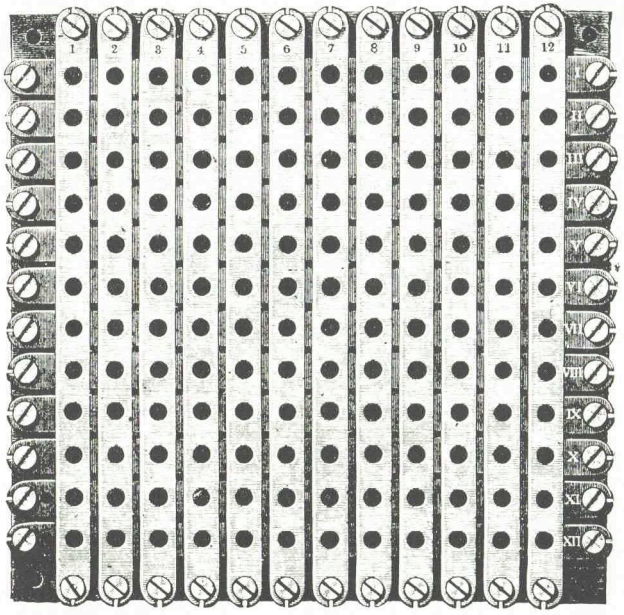
Various kinds of alarms and bells were tried as a means of alerting the called subscriber; eventually a magneto bell system devised by Thomas Watson, Bell's assistant, was adopted.

To alert the operator, an ingenious system was devised whereby the incoming electrical signal from a subscriber caused a metal shutter to fall on the operator's board corresponding to the line calling, so enabling the operator to quickly see which lines needed attention.

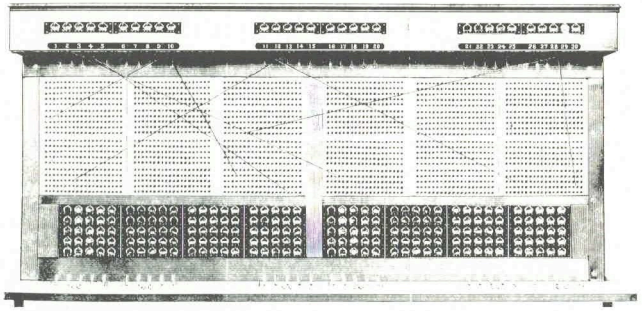
As for connecting any two lines together at the exchange, there were an enormous number of switchboard systems worked out. One of the best and most simple switchboards for a relatively small number of subscribers was that devised by Thomas Edison, who also invented the carbon telephone transmitter. It consisted of a number of horizontal metal bars insulated from an equal number of vertical bars. Each subscriber's line was connected to one horizontal and one vertical bar. Where each vertical and horizontal bar crossed in this grid there was a hole in each bar, through which the operator could push a metal plug or peg which would establish an electrical connection between the two bars at that point. If subscriber number 3 wished to speak to subscriber number 14, for example, the operator would push the plug into the hole where the horizontal bar connected to subscriber 3 crossed over the vertical bar connected to subscriber 14, so allowing electrical current to flow between them, and allowing the two subscribers to talk.



Edison grid switchboard

As exchanges became larger, however, with more and more subscribers, the number of calls become too many for one operator to handle. It became necessary to set up more than one switchboard, each handling only a portion of the subscribers connected to the exchange. The obvious problem was how to allow a subscriber connected to one board to talk to a subscriber connected to another board. Various arrangements were made to allow this to be done with lesser or greater amounts of inconvenience. But when exchanges reached a size of around a thousand subscribers, the inconvenience became too great.

A new arrangement was necessary: the multiple switchboard.



Multiple switchboard

At an exchange equipped with a multiple switchboard, every operator had a board which had access to every subscriber connected to the exchange. The Edison system of crossed bars was unsuitable for such a large number of subscribers, and instead, each subscriber had a single, unique socket on each board. The sockets were arranged in a large grid. The operator could connect together any two sockets by using a patch cord, a piece of insulated wire with a plug at each end.

The same arrangement was repeated on all the other boards at the exchange, and every board had access to every subscriber. So even if there were thousands of subscribers to the exchange, and hundreds of calls coming in every minute, the burden could be shared by as many operators as necessary.

Of course it was essential for there to be a means by which any operator could tell if a particular subscriber's line was already being used, so that she would not try to connect a new caller to it and interrupt a conversation already going on. The subcriber's socket might be unused on her own board, but she needed to know whether some other operator at the exchange had connected a patch cord to the corresponding socket on another board. Some systems just directly cut out of circuit all the other sockets corresponding to a particular subscriber's line once it was engaged on one board; others allowed the operator to test a particular socket on her board and receive a signal, perhaps a buzz or a light, to indicate whether or not it was engaged.

With the development of the multiple switchboard, manual exchanges were enabled to grow to meet the needs of larger and larger numbers of subscribers.

Eventually, however, there was a demand for exchanges themselves to be interconnected, so that subscribers could speak by telephone with people living in other towns, or in other districts in large cities. So-called "trunk" lines were established between exchanges to enable this to happen, and the operators at a particular exchange could without too much inconvenience make arrangements to connect a subscriber's line via the trunk lines to another exchange, so long as the frequency of such "trunk calls" was reasonably low. A surcharge was often made for trunk calls that made them much more expensive than a call to a subscriber on the same exchange.

Manual exchanges operated satisfactorily for many years. The operators, most of whom were female, became extremely swift and efficient at connecting lines together, and were able to provide a degree of personal service, especially in small country towns, in such ways as redirecting callers if they knew that the person being called was out of town, or by giving the time on request, and so on. Manual operators are still needed even in cities to give such personal assistance as service difficulties, directory assistance, and to provide overseas trunk calls from areas without International Subscriber Dialling (ISD).

There are still a number of manually operated telephone exchanges in rural areas of Australia today. But by about 1990, they will all have been replaced by automatic mechanical exchanges. The next sheet describes how such automatic exchanges came to be devised.

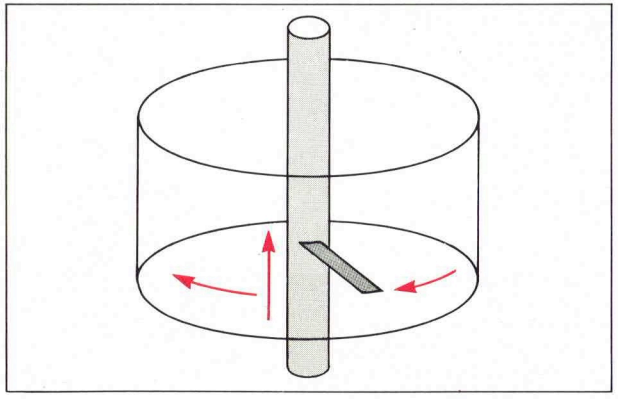
2 Almon B Strowger and the automatic exchange

No-one seems to know for certain whether or not the story about why Almon B. Strowger invented the automatic telephone exchange is true, but it is certainly true that he held a most unusual profession for an inventor. Strowger was an undertaker in Kansas City in the United States.

The story goes that Strowger's business was losing money, and he decided that the blame for this was due to the telephone system. All too often, it seemed, would-be clients asked the operator at the exchange for Strowger, but unaccountably were connected to the wrong number – which just happened to be that of Strowger's rival, the only other undertaker in the city. The explanation of these strange misconnections, Strowger thought, was to be found in the fact that one of the operators at the exchange was his rival's wife! He thereupon vowed to eliminate the human factor from telephony and invent a way of connecting lines together by purely mechanical means.

Whether this is just a fanciful story or not, it is certain that Strowger thought hard about how to set up an automatic switching system and in the late 1880s demonstrated to his nephew a model he had made from a collar-box, some pins and a pencil. He showed how, if electrical contacts were arranged on the inside of a cylinder, an arm could be arranged on a shaft or spindle so as to make connection with any of the contacts on the cylinder by the two motions of rotating the shaft or moving it an amount into or out of the cylinder.

The principle of Strowger's switch



Using vertical and rotary motions, any contact located on the inside of a cylinder could be reached by the arm.

If the subscriber could manipulate some kind of apparatus at his telephone which would mechanically operate such a cylinder and shaft at the exchange he should be able to put himself into contact with however many other lines as could be connected to the cylinder (see diagram).

The question was, how was that manipulation to be done? In Strowger's first system, patented in 1891, no less than five separate wires had to be extended from each telephone to the exchange to allow the switch to be operated. Only one of these was required for the actual telephone conversation itself (utilising an "earth return"): the other four operated electromagnets to turn and move the arm within the cylinder of contacts and complete the connection.

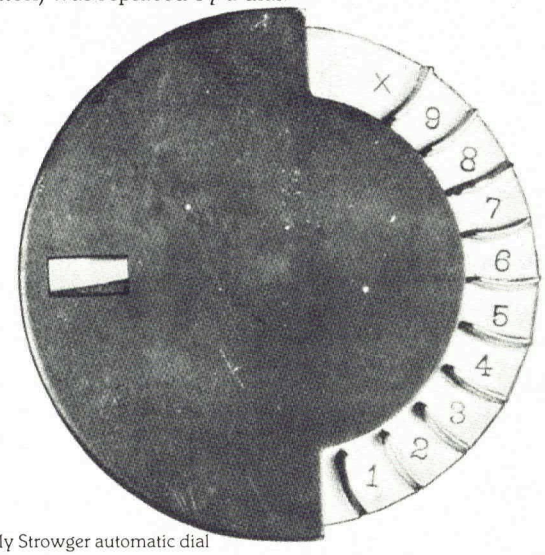
This, however, was a little impractical as it would mean that five times as many wires would need to be erected in a district served by an automatic exchange as in one with a manual exchange. The number of overhead wires around exchanges was already causing problems.

Another deficiency of Strowger's first system was the way in which the subscriber was to signal the number he wanted. There were four buttons on his telephone (each corresponding to one signal wire). Of these, the first three were used to signal the number, and the fourth to signal disconnection. Say the caller wanted to speak to the subscriber whose telephone number was 324. He would press the first button three times, the next button twice, and the third button four times. Each time he pushed a button, the switch at the exchange made one step of the movement it needed to find the required contact.

The contacts on the inside of the cylinder were arranged in ten rows of a hundred contacts each. Each time the first button was pressed, it moved the shaft carrying the contact arm up one row. The second button rotated the shaft past one group of ten contacts in that row each time it was pressed. The third button stepped the arm past one contact each time it was pressed. The combination of the operation of the buttons therefore ended by bringing the arm in touch with the specific contact required to connect the subscriber to the number he wanted.

Despite the deficiencies of the early Strowger system, the first automatic exchange using his methods opened in La Porte, Indiana in 1892.

Over the following years Strowger kept on making improvements to his system, right up to his death in 1902. The five wires out to each telephone were reduced to three by 1896 and at the same time the awkward push-button arrangement (which required the user to remember how many times he had pushed a certain button) was replaced by a dial.



Early Strowger automatic dial

The first telephone dial looks rather primitive by today's standards, but it worked on exactly the same principle as modern dials: the user put his finger in a slot corresponding to the digit required, and turned the dial until his finger reached a stop. On releasing the dial, it rotated back to its original position, and in the process sent a series of pulses corresponding to the number required along the line. At the automatic switch, each of these pulses moved the shaft one step. Subsequent numbers were dialled the same way, and the apparatus was arranged so that the pulses moved the shaft up the cylinder or rotated it, as required.

Eventually, a way was found to send dialling information along the two wires of a metallic return circuit between the telephone and the exchange, the same wires used for conversation. This is how today's systems operate.

There were still problems, though. The 1000-line automatic switch was complex and expensive to produce, and every subscriber had to have such a switch allocated to him at the exchange. And for exchanges handling more than 1000 subscribers, the size and complexity of the switch would become prohibitive. The solution was to devise a line selection procedure which operated in a number of stages.

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The way in which this worked can be understood by imagining a very simplified system based on switches able to choose any of ten lines, rather than the original complex Strowger switch, which could choose any of 1000 lines. The modern name for such automatic switches, by the way, is "selectors" (because they select between contacts), and we will use this term from now on.

Used in Strowger's original arrangement, such limited ten-contact selectors would seem to be suitable only for exchanges of ten subscribers or less. But by arranging such selectors in two or more stages, many more lines can be handled. Let us imagine a two-stage system. Each subscriber would have one primary selector allocated to him. When he dials the first digit, this selector sets up a contact not to an outgoing line, but to a bank of secondary selectors. When he dials the second digit, the dialling pulses control the secondary selector, which then chooses between its group of ten outgoing lines (see diagram). In this way, any of 100 outgoing lines are available to the caller.

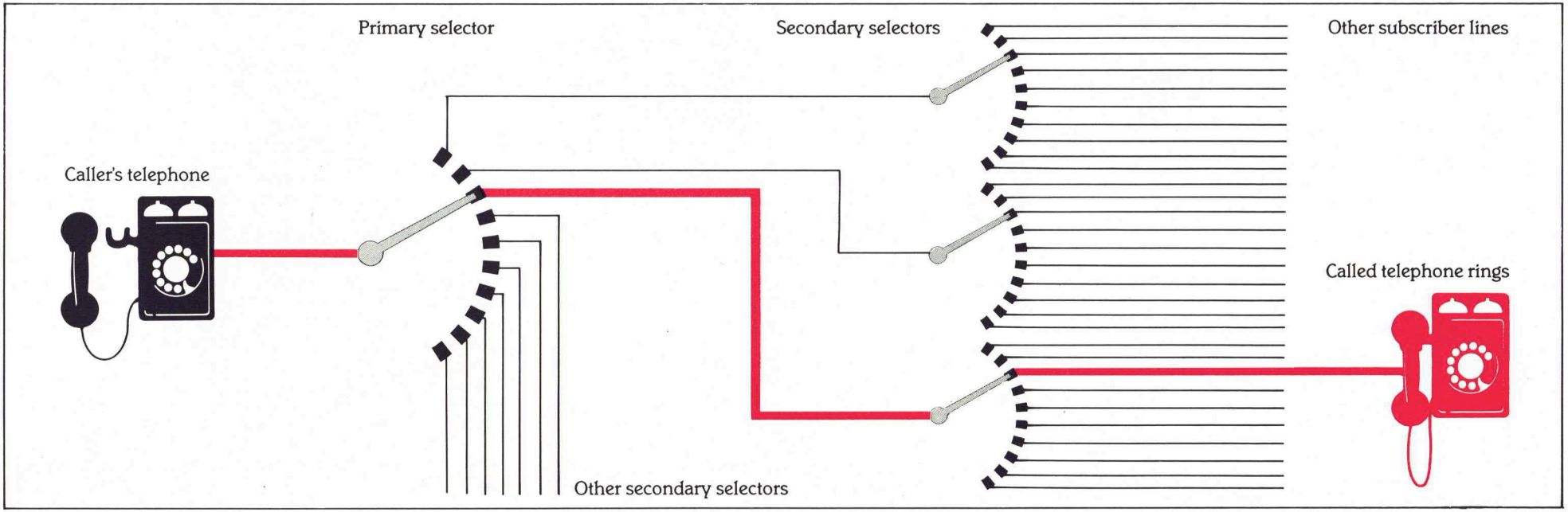
It is clear that by using three stages of selectors, any of 1000 lines would be available; with four stages, 10,000 lines; and so on.

However, although in such a system the selectors themselves could be simplified and made cheaper to produce, the number of selectors would grow enormously if whole groups of selectors had to be allocated permanently to one subscriber. For example, in a three stage system, each subscriber would need one primary selector, ten secondary selectors and a hundred tertiary selectors– a total of 111 selectors, only three of which would ever be in use at one time!

The obvious solution was to arrange the system so that all selectors other than the primary selectors could be used in common by any subscriber as needed. To enable this to work, enough selectors would have to be provided at each stage to meet the demands of the exchange at its busiest period, and a way found for the subscriber's primary selector to hunt for an unused secondary selector, passing over secondary selectors that were already in use.

The engineers of the company that Strowger founded had solved these problems by the early years of the twentieth century. An exchange opened in Augusta in the United States in 1897 which featured a two-stage switching system. In 1900, in New Bedford, Massachusetts, an exchange opened which could handle 10,000 lines, using primary and secondary selectors (each of which was capable, using vertical and rotary motions, of choosing between 100 contacts), and employing the principle of automatic hunting for an idle secondary selector.

Automatic exchanges were still some distance away from full commercial acceptance, however. The complex machinery was all too liable to breakdowns, and some subscribers were unhappy about having to set up any number they wanted themselves. Most importantly, manual exchanges still seemed efficient and uncomplicated to most people who did not share Strowger's bias against the telephone operators and moreover, the cost of employing the female operators was low. But as the number of subscribers grew, and manual switchboards became choked, it began to become clear that eventually automation was the only way that the increasing numbers of calls could be handled.

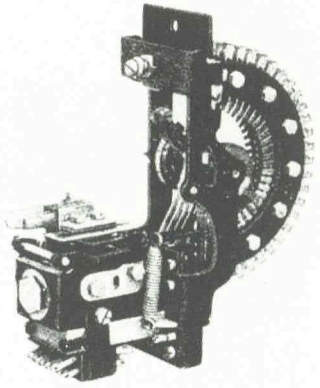


3 The progress of a call through a step by step exchange

In order to give you a better idea of how an automatic exchange of the Strowger type operates, we will follow a call being set up and connected. Such exchanges are often called "step-by-step" exchanges, because each digit dialled sets up another step of the call.

Let us imagine a small exchange such as might have existed in the earlier days of automatic telephony in this country. Subscribers connected to this automatic exchange all have telephone numbers of four digits only, for example 2345 or 7654. Up to 10,000 subscribers could be connected to such an exchange. The exchange uses selectors which have two motions–vertical and rotary–and which are therefore called "bi-motional" selectors.

The exchange incorporates one more refinement than those very early exchanges we discussed in Sheet 2. Instead of each subscriber having his own expensive bi-motional first selector, he is allocated a much simpler selector which only has one kind of motion– a rotary motion along a row of contacts. This simple selector, called a uniselector, carries out the hunting function and finds a free first selector when a call is being made. In other words, the first selectors too are placed in a common pool, and therefore their number (and the expense) can be reduced. This refinement was introduced in 1904 by an American engineer, Alexander Keith, and helped make Strowger exchanges a commercial success.



A uniselector

So a subscriber to this exchange wants to make a call. To begin with, he lifts the handpiece of the telephone. This allows a spring-operated switch in the telephone to close, and the current flowing in the line tells the exchange that the subscriber wants to make a call.

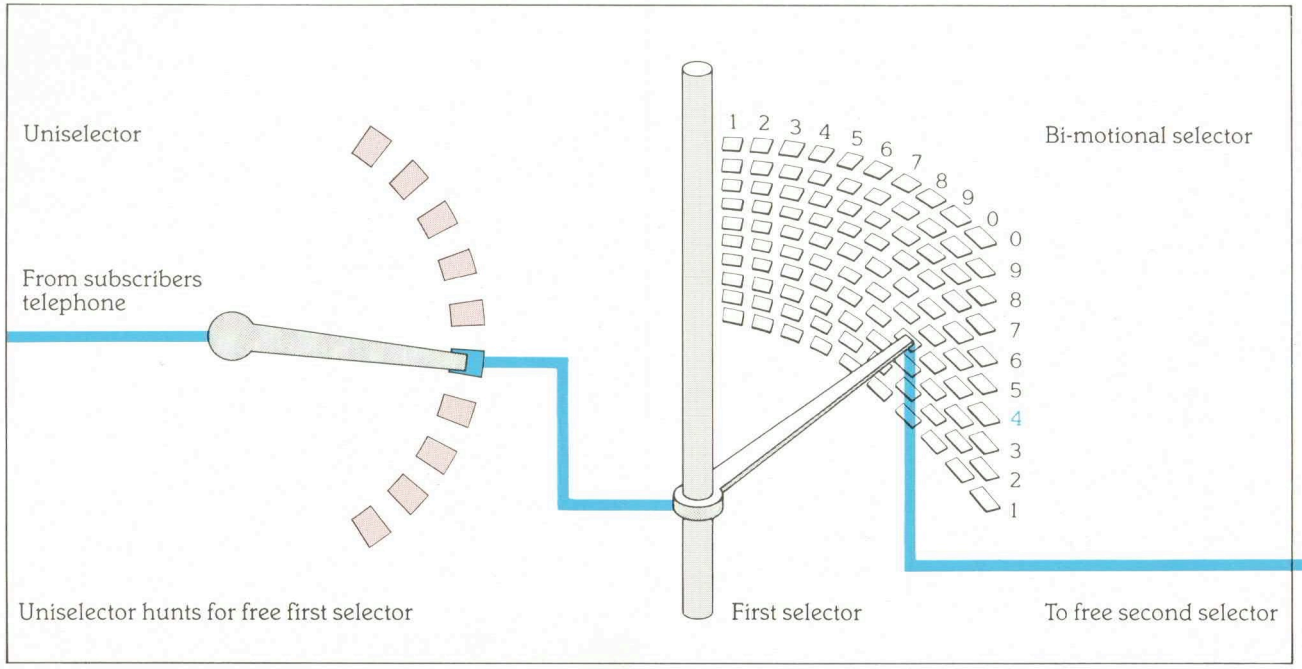
As soon as the exchange receives the signal from the subscriber's telephone, the arm on the subscriber's uniselector starts wiping over each of the contacts in turn, looking for a free first selector. If the first selector connected to a particular contact of the uniselector is already being used by another subscriber, the uniselector passes it by, stopping only when it reaches a contact connected to a free first selector.

When that occurs, special equipment at the exchange is connected to the subscriber's line to send him the "dial tone", a sound which indicates that he is now free to dial.

All of this happens within a fraction of a second, so that the subscriber is usually not aware of any delay in obtaining the dial tone after picking up the handpiece.

Let's say that the number he wishes to ring is 4388. His line is now connected, through the uniselector, to a free first selector. He dials the first digit, a "4". The movement of the dial back to its rest position interrupts the steady current going down the line four times, in this way sending a signal to the equipment at the exchange.

The selectors at the exchange, except the uniselectors, are all of the bi-motional type, and have ten rows of ten contacts each. The arm of the selector can move up and down the rows, and be rotated around each row of contacts. When the four pulses from the subscriber's dial reach the first selector, the arm is stepped upwards one row for each pulse, and so in this case ends up at the fourth row. The arm then proceeds to rotate across the ten contacts in that row, each of which is connected to a second selector. As with the uniselector, the arm of the selector will test each contact in turn, and stop only when it reaches a contact connected to a second selector which is not in use by anyone else. Again, this all happens in a fraction of a second, before the subscriber begins to dial his second digit.


Uniselector
From subscribers telephone
Uniselector hunts for free first selector
First selector
Bi-motional selector
1 2 3 4 5 6 7 8 9 0
0 9 8 7 6 5 4 3 2 1
To free second selector

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The subscriber's line is now connected through the uniselector, through the first selector, to a second selector in the group which is allocated to handle numbers beginning with "4". He dials the next digit, a "3". The arm of the second selector moves up to the third row and begins hunting across that row for a free third (and in the case of this exchange, a final) selector. These final selectors are of the group which is allocated to handle numbers beginning with "43".

Now because numbers connected to this exchange only have four digits, this third selector to which the subscriber now has his line connected is the last stage, and it does not need to carry out the hunting process to find another free selector. For this reason, a hundred outgoing lines can be connected to it.

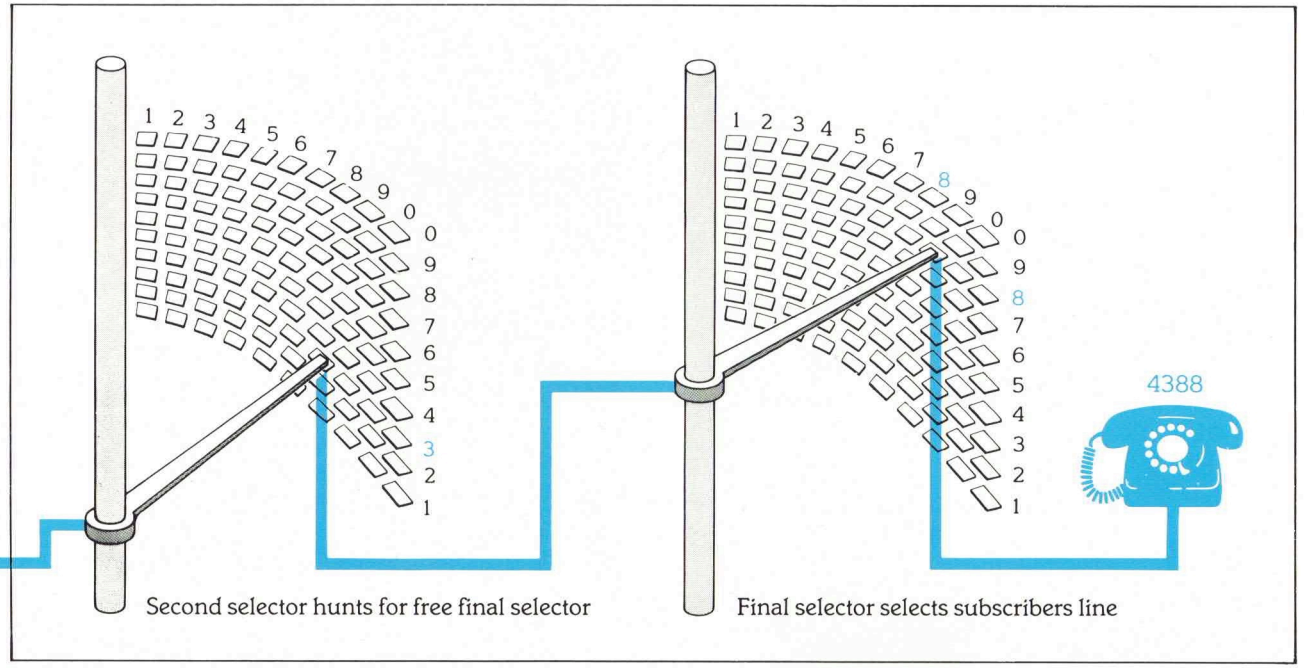
When the subscriber dials the next digit, an "8", the arm of the third selector steps up to the eighth row of contacts, but does not move apart from that. Then when the final digit, an "8" is dialled, the arm of the selector rotates to the eighth contact in that row, which is connected to the line of subscriber number 4388.

The exchange then tests to see if this line is currently engaged on another call. If it is free, then equipment to generate the "ringing tone" is connected to the calling subscriber's line, and current is sent along the line of the called subscriber to ring the bell in his telephone. Once the called subscriber answers, all equipment other than the selectors is disconnected from the two lines, and the two subscribers may talk.

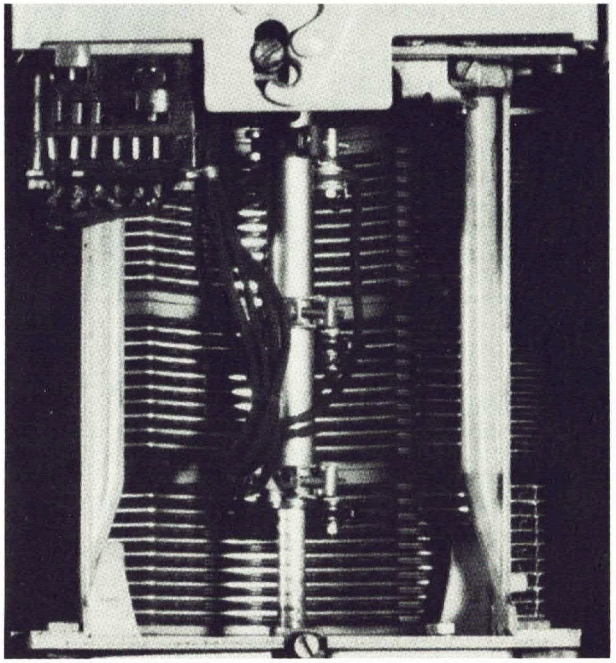
If the wanted number had been engaged, then the "engaged tone" would have been sent along the line of the calling subscriber. The same tone would have been sent if at any stage during the process, a free selector could not be found. But the number of selectors at the exchange is chosen very carefully so that this kind of "traffic jam" should happen only very rarely when the exchange is extremely busy. Today, most telephone numbers in city areas have at least six digits and this means that with a step-by-step exchange, there would be many more stages, and many more selectors required. However, the principles we have just described remain the same.

It is important to note that the description given above is of a call between two subscribers to the same small local exchange. In a metropolitan area, calls may need to pass through several exchanges in order to link subscribers in more distant areas of the city. In such a system, the first few digits dialled by the caller connect his or her line, not to another selector in the local exchange, but to an outgoing line to another exchange. So, in a number such as 435-6789, the first three digits are called an "exchange prefix", which tells the switching equipment how to route the call to another exchange. There are also special exchanges called trunk and tandem exchanges whose sole function is to act as a link between other exchanges for such calls between distant subscribers.

Step-by-step exchanges are still in use all around Australia. But they are being steadily replaced by much more sophisticated and more modern automatic exchanges. We will discuss the first of these in the next sheet.



Close up of a bi-motional selector (step by step equipment)



4 The principle of common control and crossbar switching

In any method of telephone switching, there has to be a form of control system to connect lines together under the instruction of the caller, and to disconnect them when the call is finished. Certain other tasks are involved, such as finding out if the wanted line is free, and so on.

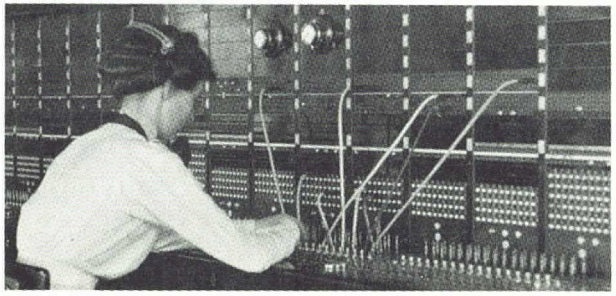
In the step-by-step system, control is in effect built into the various selectors used during the call. The caller dials each digit of the wanted number in turn. Each time he or she dials a digit, a selector at the exchange operates to connect a path to another selector which will then be ready to accept the next digit from the caller. The connection is set up step-by-step. All of the selectors used in setting up the call must be held as they are until the call is over, a period which could be minutes or even hours in an extreme case.

This represents some degree of waste and inefficiency. Bi-motional selectors are complex, electro-mechanical devices which are expensive to make and which are somewhat liable to breakdown. This complexity, expense and need for maintenance could be greatly reduced if it were possible to separate the control system from the switching mechanisms. In such a system, the control devices would be used only very briefly during the setting up of the call, after which they would be free to go on to set up another call while the first call continued.

This is the principle of common control, and it is the basis of all modern exchange systems.

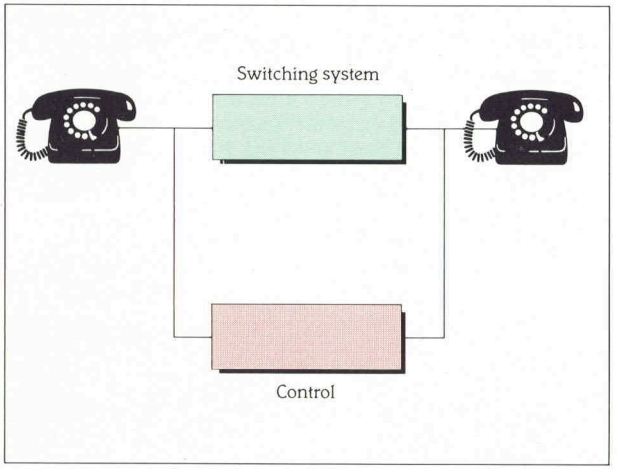
As one way of illustrating the principles involved, it will be useful, paradoxically, to skip back in history beyond the Strowger system and to think about a manual operator at an early exchange.

We can easily see that in such a manual exchange, the intelligence of the operator provides the control system quite separately from the switching mechanism, represented by the switchboard with its plugs and sockets.



The operator is alerted to an incoming call, listens to and remembers the wanted number, finds the appropriate way of connecting the caller to the wanted line, makes sure that the line is not busy, and finally makes the connection. At that point, she is free to connect other calls while the first call continues.

In a very similar way, in a common control exchange (such as a crossbar exchange, which we will describe in more detail later), the control system in a sense sits to one side of the switching mechanism, controlling it as required. We will see, too, that in such an exchange the control system "remembers" the required number before taking any other action.



There are many advantages of using the principle of common control. Firstly, as we have discussed, the switching mechanisms themselves can be made much simpler and cheaper. Although the control devices are much more complex, only a few of them need to be provided, since they are only needed for a brief period of time. There are consequent savings in space and maintenance.

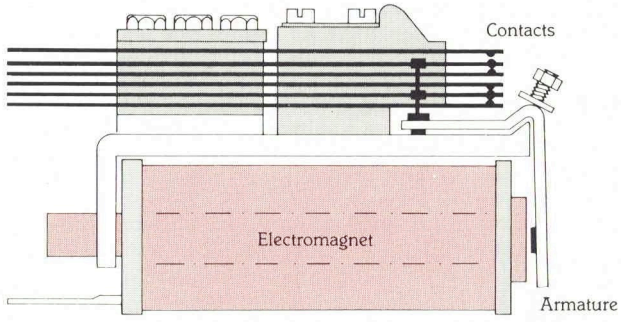
Secondly, the switching system becomes to a degree independent of the numbering system. In a step-by-step exchange, the telephone numbers allocated to the subscribers served by that exchange are "wired in" to the arrangement of selectors. The numbers used for exchange prefixes, in a network of step-by-step exchanges, are also in a sense fixed to certain areas by the arrangement of switching equipment. With common control exchanges, number allocation can be much more flexible.

So far we have talked about common control exchanges in general. But it was with the introduction of crossbar switching that the principles of common control were first used on a large scale in Australian exchanges. Crossbar exchanges now make up a very large part of our switching network. So it is time to look at the development of the crossbar switch.

The basic principle of crossbar dates back to the early Edison manual switchboard described on Sheet 1, which used a grid of vertical and horizontal bars which could be connected together by pushing a metal plug through holes at their cross-over point. Each subscriber's line was connected to both a vertical and horizontal bar, and since in such a co-ordinate arrangement every vertical bar crosses every horizontal bar at some point, any two subscribers could be connected together by making the connection at the appropriate cross-over point.

In 1912, the Swedish engineer Gotthief Betulander patented an automatic switching system based on a co-ordinate arrangement of electro-magnetic relays. Instead of a plug being pushed in manually at the cross-over point of vertical and horizontal lines, in Betulander's system there was a relay at each cross-over which would close when required to make the desired connection.

A relay basically consists of an electro-magnet (which attracts only when current is passing through its coil) and an armature (a piece of iron which moves when attracted by the magnet). The relay is so arranged that when a small current passes through the electro-magnet, the armature moves and brings together contacts through which another current can flow:



A typical telephone relay

4 The principle of common control and crossbar switching

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The great advantage of Betulander's system over the Strowger system of automatic switching (which by then was well established) was that there was no selector arm moving up and wiping across contact points. The only moving parts were the armatures of the relays, which moved only a few millimetres to bring contacts together, and therefore the reliability and freedom from maintenance of his system was potentially much greater. The cross-point relays could also operate much more quickly than the complex bi-motional selectors of the Strowger system.

On the other hand, the major defect was that Betulander's system as it stood was really only suitable for small exchanges, just as Edison's manual switchboard was only suitable for a small number of subscribers. Because these systems used a square grid arrangement, the number of cross-over points (and therefore relays in Betulander's system) increased as the square of the number of subscribers. For example, with 10 subscribers there were 100 cross-over points. Doubling the number of subscribers to 20 meant that 400 cross-over points were needed, quadruple the number for 10 subscribers.

Relays of the early type used by Betulander, though much cheaper than the complex Strowger selectors, were nevertheless not cheap to make, and the need to provide very large numbers for even a modest size exchange meant that it was not economic to use Betulander's early system for any but small and usually remote exchanges (where the need for unattended equipment to run automatically for a long time without maintenance was paramount).

However, Betulander found a way to use his system more economically. Instead of using a single large grid of relays, it was found possible to interconnect a number of small grids in a series of switching stages and so substantially reduce the number of relays needed to connect the same number of subscribers together. Also, a new and much cheaper kind of relay was developed in 1936–the reed relay. These developments made relay automatic exchanges much more economic, and with the development of electronic control systems after the Second World War, such exchanges could be made large enough to handle the telephone traffic of cities. A number of such exchanges have been built in Europe since the 1960s and reed relay switching was incorporated in computer-controlled trunk exchanges introduced into Australia during the 1970s.

The line of development of such reed relay exchanges, however, differs somewhat from the development of the crossbar switching system. Nevertheless, Betulander's early principles were drawn on by the Swedish engineers who designed the crossbar switch in the 1930s. Crossbar exchanges were first introduced into Australia in the late 1950s.

Without going into the details of the common control equipment used in the crossbar system (the functions of which will be described on the next sheet), we can now look more closely at the crossbar switch itself.

Unlike Betulander's grids with a relay at each cross-over point, the crossbar switch consists of a number of vertical and horizontal bars, each moving under the control of one electromagnet in the case of the vertical bars or two magnets in the case of the horizontal bars. The movement of the bars controls the opening and closing of various sets of contacts, a unique set of contacts being associated with a particular position of vertical and horizontal bars.

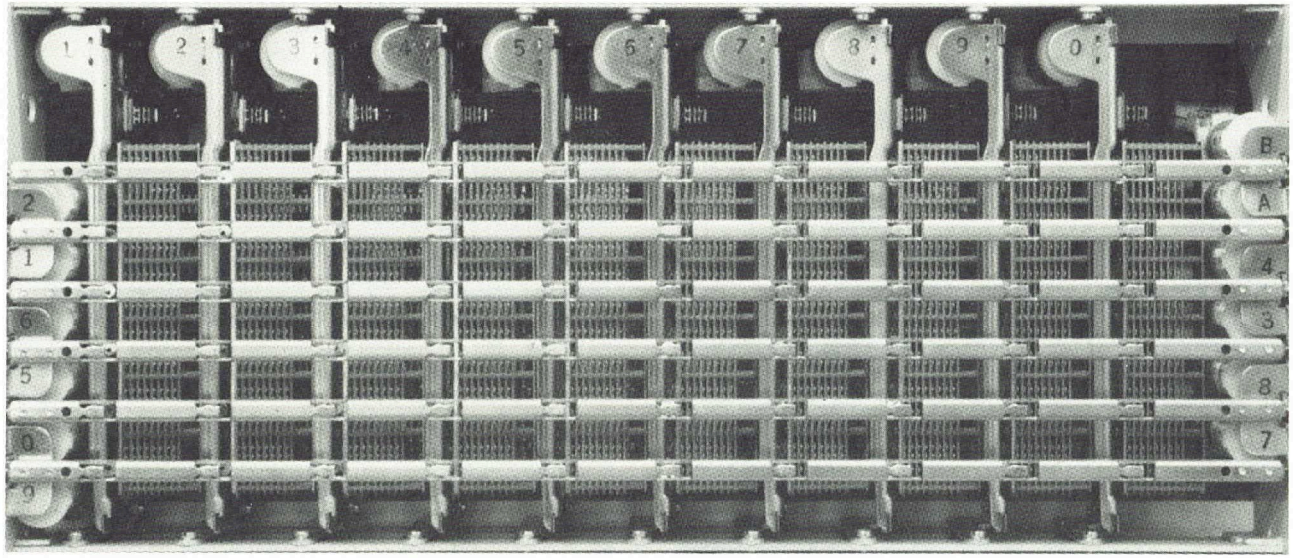
A typical switch might have ten vertical bars and six horizontal bars. Such a switch would be capable of connecting any of ten input lines to any of twenty output lines. This is possible because of the way the switch operates. The two magnets on each horizontal bar enable it to be tilted either slightly upwards or downwards. The two positions of the top horizontal bar select between two separate groups of ten outlets each, and one of the other five horizontals can then be tilted either up or down to select the correct output from among this group of ten.

It is important to note here that when we speak of one input or output line, this line may consist of up to five wires, all of which are associated with the speech path and control circuits for the subscriber's line within the exchange.

When the switch is operated, the horizontal relays operate first, and then one of the vertical bars moves. Once the vertical bar operates (selecting one of the ten input lines to the switch), the connection between input and output lines is held fixed, and the horizontal bars can then return to their normal position. The connection will not be broken until the vertical bar is released. This means that the horizontals are free to establish connections with inputs on other verticals while the first connection remains held.

In a crossbar exchange, such crossbar switches are arranged in a number of stages to enable very large numbers of lines to be connected together.

A major innovation which the introduction of crossbar switching in trunk exchanges made more practicable was Subscriber Trunk Dialling (STD). This meant that by dialling a special "area code" first, callers could be simply connected to more remote areas without the need of a manual operator's assistance. In effect, the area code was a higher-level exchange prefix. The STD code digits connected the caller through to trunk lines.



Close up of a crossbar switch

5 The progress of a call through a crossbar exchange

The crossbar switch described on the previous sheet can of course do nothing by itself. It must operate under the control of other devices which provide the common control system of the exchange. The most important of these devices are called registers and markers. In particular, it is the markers which use the switching equipment to find a free path for the transmission and control of a telephone call. The major function of the registers, on the other hand, is to "remember" the wanted number and to send and receive control signals from the markers to make the required connection.

The following description of the progress of a call through a crossbar exchange is of necessity rather complex, and if you wish, you could skip past this sheet to the next if it becomes too difficult.

There are a number of different kinds of crossbar exchange, as you might expect, but the one we will consider is a type used in Australia called an ARF exchange, designed in Sweden by the L. M. Ericsson company. Trunk exchanges using this technology are called ARM exchanges. (The initials are abbreviations of Swedish words, so there is no point in giving them here.)

It would be impossible in so little space to describe the operation of the exchange equipment in anything but very general terms, but it is worthwhile remembering that each piece of equipment described is a complex and sophisticated electro-mechanical device.

First of all then, someone picks up the handpiece of their telephone. As in the step-by-step system, this allows a spring-operated switch in the instrument to close and current flows on the line to the exchange. A set of relays is associated with every subscriber's line, and these detect whether current is flowing or not.

The flow of current operates a relay to connect the line to the first marker, called the subscriber line marker. There is one of these markers (or occasionally two, in heavy traffic situations) for each group of 1000 subscribers and it can only handle one call at a time.

The first thing the marker does is to identify which of the 1000 lines under its control is making the call. It then uses two crossbar switching stages to find a free path between the calling subscriber's line and a device called the subscriber's relay set. As there are only a limited number of subscriber relay sets allocated to each group of 1000 subscriber lines (between 75 and 150 depending on the traffic load), the marker must carry out a "hunting" function similar to that of the selectors in a step-by-step exchange in order to find a free set.

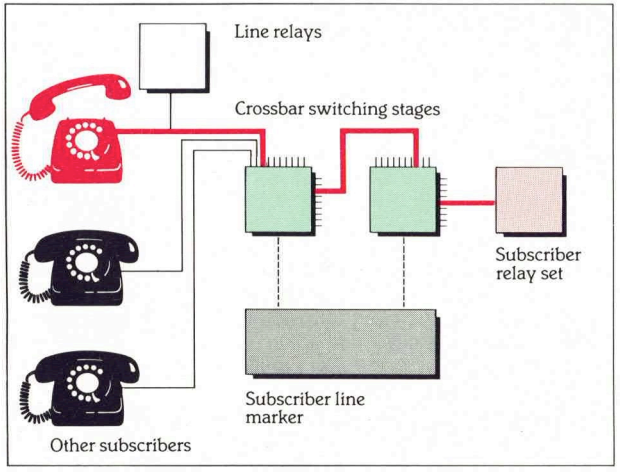
The subscriber relay set is responsible for carrying out a number of important functions, and it is required throughout the entire call. It supplies current to hold the magnets of the crossbar switches in their final position; supplies current to one or both telephones involved; transmits ringing current and ringing tone; and carries out metering as well as providing a transmission path for speech. Of course it does not do all of this at once, as we shall see.

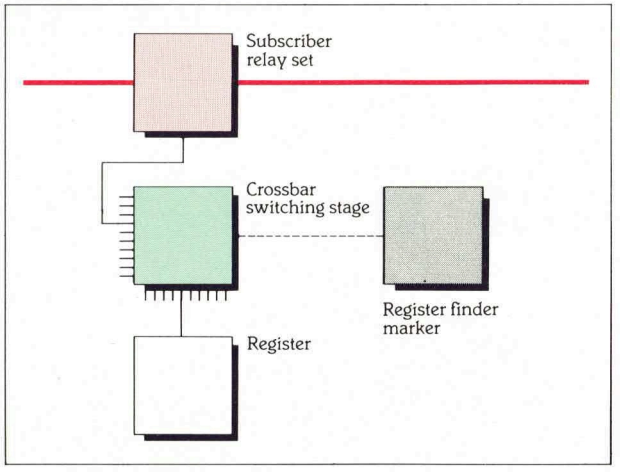
Once it has found a free relay set, the line marker operates the crossbar switches to make the connection to the subscriber's line, and then calls the next device, called the register finder marker, up to three of which can be allocated to each group of 1000 subscriber lines. As the name suggests the function of this marker is to find a free register and to connect the subscriber's line to it (through the subscriber relay set being used for the call). To do this, it has a crossbar switching stage under its control.

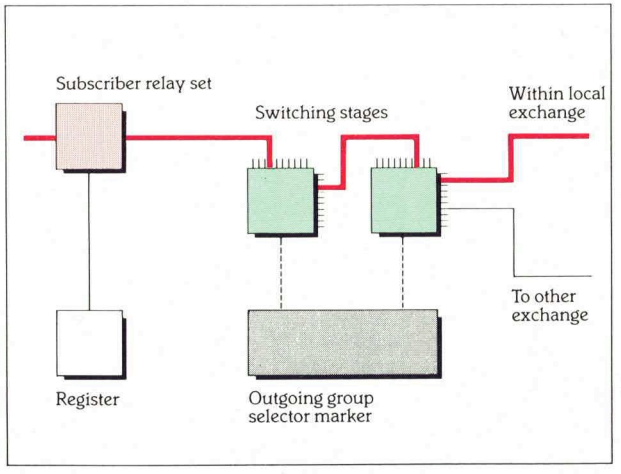
Between 75 and 120 registers are normally allocated for every 10,000 lines. Once a free register has been found, both the register finder marker and the subscriber line marker drop out, and are then free to handle other calls.

The first thing that the register does is to transmit the "dial tone" to the calling subscriber's telephone. All of this complicated activity so far has been carried out in a fraction of a second. When you pick up the handpiece of your phone, the dial tone seems to be there immediately without any delay. But despite appearances, as you can now see, the exchange has been very busy!

The caller can now proceed to dial the wanted telephone number. At this point there is a major difference in the operation of a step-by-step exchange and a crossbar exchange, because it is the register's function to accept the dialling pulses from the subscriber and to "remember" or store the whole or part of the wanted number before taking any other action.







5 The progress of a call through a crossbar exchange

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The register then calls in an associated device to enable it to transmit and receive special code signals to and from the next marker involved. This next marker is called a group selector marker, and there are several such markers allocated to the outgoing stage of the exchange.

The outgoing group selector marker has identified which subscriber relay set is being used for the call, and now receives digits from the register and analyses them to determine how the call must be routed, depending on whether it is a local call (that is, to another subscriber connected to the same exchange) or one which will need to be connected through other exchanges, or is even an STD call to a distant exchange area. It then sends appropriate control signals back to the register.

The group selector marker operates up to three switching stages under its control to connect the subscriber's line on to the next stage, either within the same exchange, or out along trunk lines (or "junctions") to other exchanges. For simplicity, we will consider a local call only.

The next stage, whether it be for a local call or for a call coming in to an exchange from some other exchange, is the incoming group selector stage, which is almost identical to the outgoing stage. The outgoing marker drops out once communication is established between the register and the incoming group selector marker and of course is then free to handle other calls.

The incoming group selector marker then takes further digits of the wanted number from the register to allow it to control its switching stages to find the correct group of 1000 subscribers in which the wanted line will be found. Once it has found a free path to this group, it passes control to the subscriber line marker in control of that group, and drops itself out to handle other calls. Again, all of this activity has taken only a fraction of a second after the last digit was dialled by the caller.

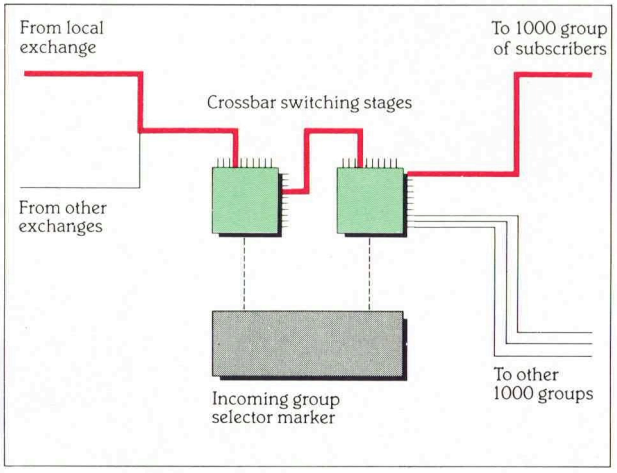
The subscriber line marker accepting the incoming call is exactly like that involved for outgoing calls; the same markers perform both incoming and outgoing functions for their group of 1000 subscribers. However, on an incoming call, the marker controls four crossbar switching stages, and this enables it to locate the exact line wanted by the caller and set up a connection to it, under the control of the last digits sent to it by the register.

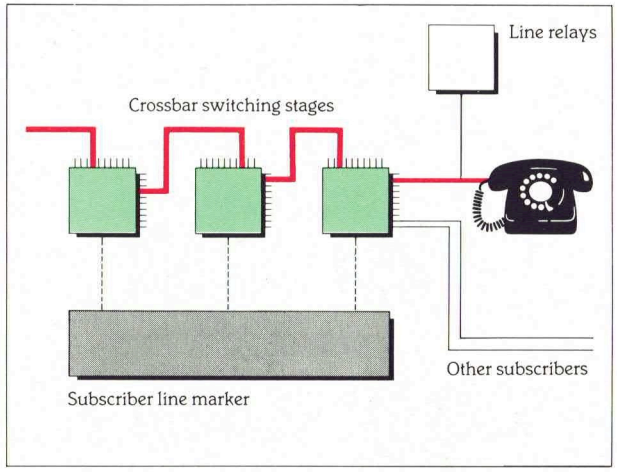
The line relays on the wanted subscriber's line are then tested to let the register know if the line is free or busy. If it is free the relays are operated and the register switches the subscriber relay set into a particular mode suitable for handling the call, depending on whether it is a local call, or one to other exchanges of various types. The register then drops itself out. At this point there is a connection between the caller's line and the relay set and between the relay set and the called subscriber's line.

The subscriber relay set sends a current along the called subscriber's line to ring the bell in his or her telephone and at the same time sends "ringing tone" along the caller's line to let him or her know that the wanted phone is ringing. Once the handpiece of the wanted phone is lifted, ringing current and tone are disconnected by the subscriber relay set. Finally, the two subscribers can talk to each other!

Of course, all of this has taken much longer to describe than it does to actually happen. In particular, each of the markers involved only operates for a fraction of a second, which means that it is practicable for calls to "queue up" for them if they are busy, and so only a few of each kind need to be provided for many subscribers. The register has to be involved for a relatively longer period, while the call is dialled and set up, so the delays in waiting for one would be unacceptable, and therefore more of them have to be provided than markers.

While the conversation continues, nothing much happens as far as the exchange is concerned (of course, it is busy setting up dozens or hundreds of other calls). But when the caller puts down the telephone handpiece, the subscriber relay set is released, though not before it has sent signals to the caller's meter to tell it that the call is over, and to complete the charging of the call. If the called subscriber puts down the handpiece first, there is a delay before the connection is broken. This allows the called person to go to another (perhaps more convenient) telephone extension without losing the call.





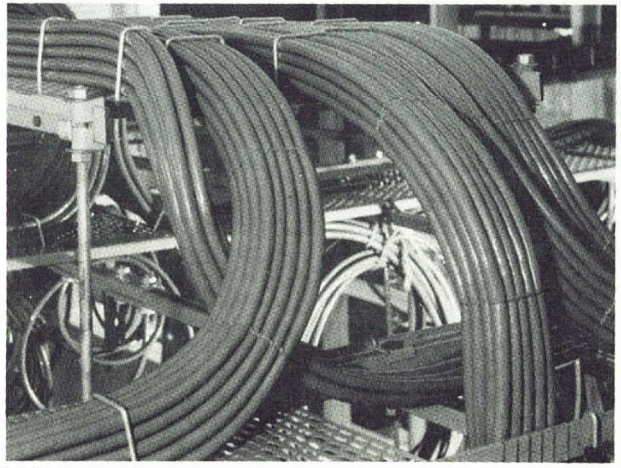
6 A typical telephone exchange

We can now look at the operation of a typical modern telephone exchange. Although we have talked in some detail about the switching operations involved, no exchange could operate properly if all it contained was switching equipment.

A local exchange, such as one in a suburb or a small town, is at the centre of thousands of wires radiating out to the telephones of every subscriber it serves. Each telephone service requires a pair of wires. In the early days of telephony, all of these wires were carried overhead, on poles. But as the telephone became popular, the sky became filled with myriads of wires, and telephone exchanges had to have enormous derricks erected on their roofs to collect and support all of these wires as they came into the exchange.

Today by far the majority of telephone lines, and certainly those in the central areas of cities, are in underground cables capable of carrying thousands of wires. The cables are carried through ducts beneath the streets. They come in to the exchange in its basement, and onto a main distribution frame, from where the wires are separated into groups in smaller cables and distributed out to the switching equipment.

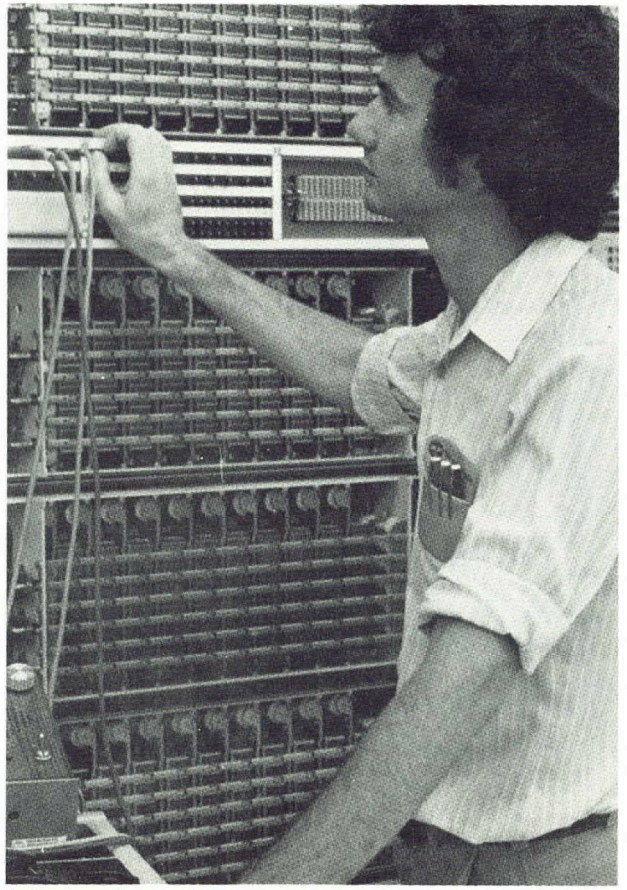
The complexity of the wiring involved in even a small exchange is staggering. Cables run from the distribution frame and onto overhead grids in the switching equipment rooms, fanning out to the appropriate piece of switching equipment.



Cabling on top of racks at an exchange

In many older exchanges, particularly the larger ones in cities, step-by-step equipment exists side by side with the newer crossbar equipment, and arrangements have to be made to allow the two types of switching gear to work together.

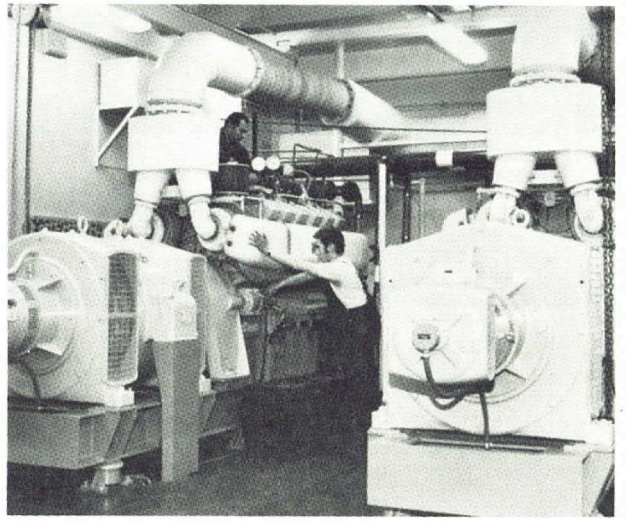
The switching equipment itself is arranged in vertical racks with aisles between them for ease of access. With step-by-step equipment, the sound of the selectors moving as people dial can be continually heard. In a crossbar exchange, the equipment is much quieter and more compact, the relays and switches being kept behind glass panels to exclude dust.



Testing a crossbar switching stage

The electrical power to operate all of this equipment usually comes from the mains supply, although before it is used it must be converted from the alternating current (AC) supplied by the mains to direct current (DC), which is more suitable for operating electromagnets and relays. Direct current is also supplied by the exchange to all of the telephones it serves.

The exchange has a battery room, full of very large batteries rather like those in a car. These batteries are kept constantly charged by the mains, and it is from them that direct current is drawn for the operation of the exchange and telephone instruments. This is why the telephone service is usually still available when other services stop due to a power blackout. At most large exchanges, if the mains supply fails an electrical generator automatically starts up to keep the batteries constantly charged.



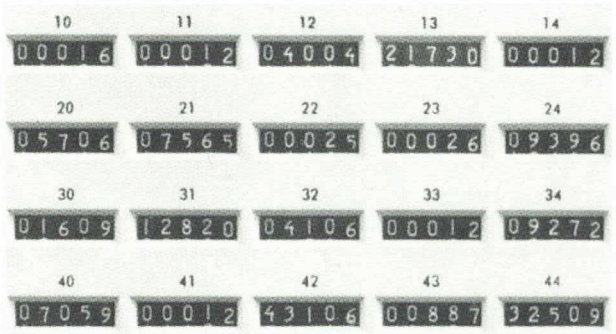
Electrical generator and diesel motor in a telephone exchange

There is another part of the exchange which is very important, and this is the meter rack. Keeping the telephone service operating efficiently costs a lot of money, so a charge is made for use of the service. This is in two parts, a basic rental charge to cover the cost of maintenance, not just of the telephone instrument, but also of the exchanges and the network. The second part of your telephone bill is a charge for each call made, so that the heaviest users of the system are those that pay the most. To allow this charge to be worked out, all telephone calls are registered on a meter.

6 A typical telephone exchange

Telecom Australia

In the meter rack there is a small meter like a car distance meter for every subscriber. Every time a subscriber makes a successful call (that is, the caller did not receive an engaged signal or other problems, and the called telephone was picked up), the meter registers the call. If the call was a local call, then the meter just clicks over once at the end of the call. But if the call was an STD or ISD call, the meter clicks over a number of times at a rate depending on the distance of the call, the time of day, and the day of the week. For the most expensive international calls, the meter would click over every few seconds. For the longest-distance interstate call in Australia during business hours, the meter would be clicking over perhaps six times a minute. For a short distance STD call at the cheapest time, the meter would click over only about once every four minutes.

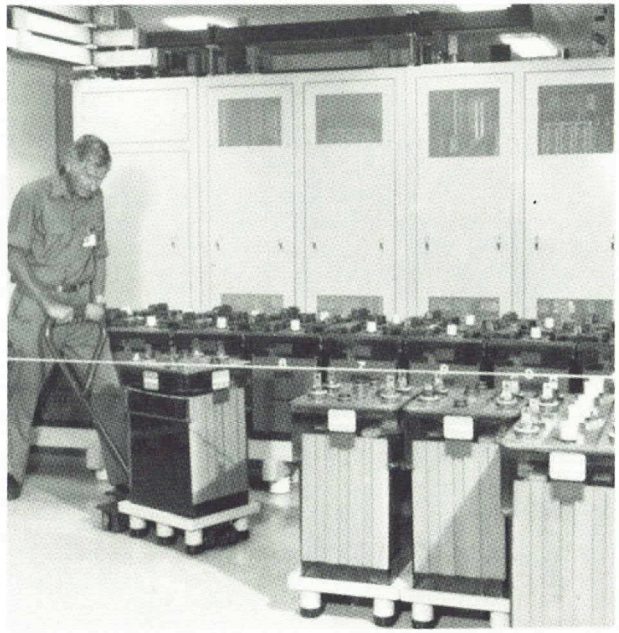


Meter rack showing subscriber's meters

Every effort is made to avoid errors in reading meters, and as part of this, the meters are not just read and noted down, but photographed in blocks with a special camera. The negatives produced by this process are then read and entered onto a computer terminal at a later date.

In future, with the very modern exchanges described on Sheet 7, it will be possible to update the metering system remarkably, and it will be possible to provide full details of STD calls made, for customers who arrange for this in advance. At present, this is not possible because of the metering system, where one meter must record all of the telephone usage whether for local calls or for STD calls. Some new exchanges already allow ISD calls to be recorded separately.

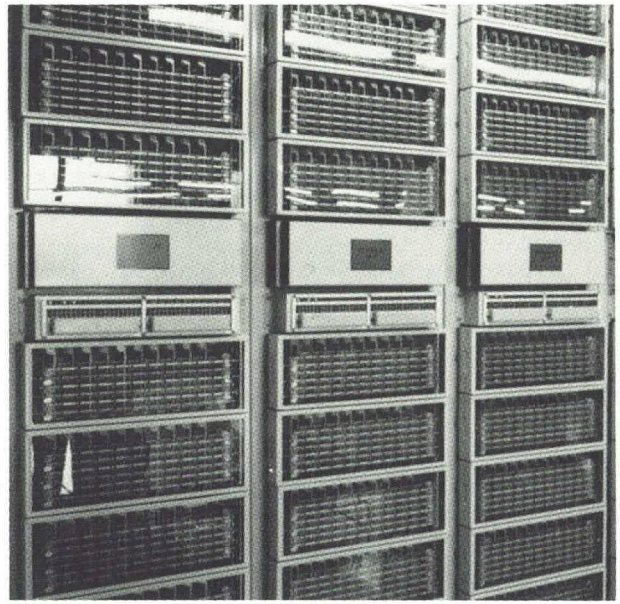
Keeping the exchange operating efficiently is of course very important, and tests are constantly run (usually late at night, when telephone traffic is at its quietest) to check out the switching equipment for faults. Any faulty equipment is isolated and repaired. Step-by-step equipment is of course most liable to failure, involving as it does many moving parts which have to make large-scale movements. Crossbar equipment is much more reliable, and computer-controlled exchanges will be the most reliable of all. But checks are of course still needed to make sure the telephone service keeps operating at peak efficiency at all times, and Telecom employs many skilled technical staff for this purpose.



Positioning batteries at an exchange

The meters are also checked regularly to make sure they remain accurate. The accounts of all customers are monitored, and if an account is ever much larger than the average for that customer, special checks are made.

One final aspect of larger exchanges may seem surprising, and that is the security control. Our society depends heavily on rapid telecommunications, and immense problems could be caused by the destruction of equipment at a large city exchange by, say, terrorist action. So there are security guards at these exchanges to check on visitors and protect the exchange.



Racks of crossbar switching equipment

7 The computer comes to the exchange

All of the switching control functions in crossbar exchanges were carried out, until quite recently, by complex pieces of electromechanical equipment. The registers and markers were made up of sophisticated arrangements of relays and switches to carry out mechanically the operations involved. The crossbar switch itself is an ingenious mechanical device, controlled by the operation of electromagnets.

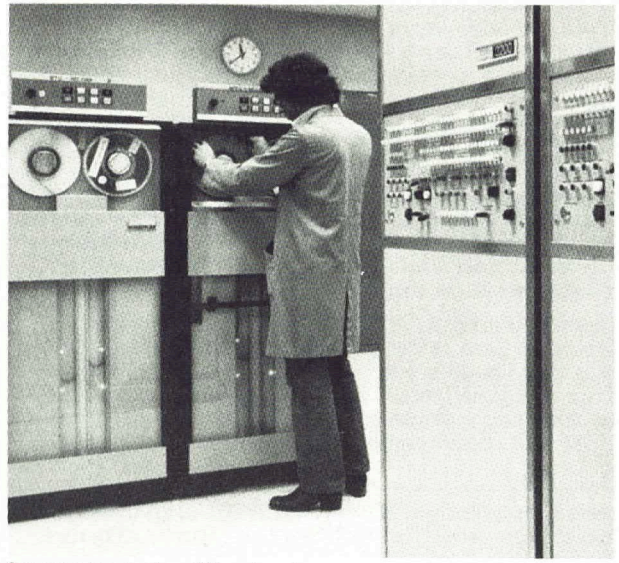
However, with the increasing development of computers and electronic technology in general, it became clear in the last few decades that many of the control functions of a telephone exchange could be carried out more efficiently by computers, or by miniaturised computers called microprocessors.

The first electronic computers were developed towards the end of World War 2, to assist in code-cracking and in ballistic calculations (how to angle guns so as to accurately fire shells at targets). These early machines were gigantic by today's standards, made up of thousands of radio-type valves and complicated wiring. To set up the series of mathematical calculations required (what today is called "programming") meant that hundreds of connections had to be re-arranged. The heat generated by the valves was extreme, and breakdowns were common.

In the intervening decades, all of that has changed. With the invention of the transistor in 1948 by workers at Bell Telephone Laboratories, the bulky, hot and inefficient valves could be replaced by compact solid-state devices which were much more reliable.

This enabled computers to become much more sophisticated, cheaper and rapid in operation. Modern computers can carry out an enormous number of mathematical or logical operations in a fraction of a second, as well as accepting signals from the outside world, analysing them, and sending back control signals. They do this by strictly following a list of very explicit instructions called a program, which is stored in a part of the computer called the memory. For this reason, computer control of an exchange is sometimes called Stored Program Control (SPC).

The first introduction of such techniques for telephone switching in Australia was with the establishment of computer-controlled major trunk exchanges in Sydney, Melbourne and Adelaide during the mid-1970s. These exchanges, called Metaconta 10C exchanges, used reed-relay cross-point switches under the control of a large computer to route trunk calls to their correct destination, and provided very much more sophisticated facilities for manual trunk operators.



Computer in a modern 10C exchange

Miniaturisation in electronics has continued to an almost incredible extent, and indeed, this process is still going on. Today many thousands of transistors and other electronic components can be fitted onto a tiny chip of silicon no bigger than a fingernail. Quite small devices can now carry out very sophisticated control functions.

In order to improve the operation of crossbar exchanges, and to provide a range of new subscriber services, such electronic equipment is being installed. The register and some of the markers are replaced by electronic components on printed circuit boards. These are under the control of a small central computer, which divides its time between them, controlling their operation as required.

ARF crossbar exchanges which have been modified in this way are called ARE-11 exchanges, and the first installations of such equipment in Australia were in 1977. The modification of exchanges with this equipment is now proceeding strongly, and it is anticipated that ARE-11 exchanges will form a major part of the switching network well past the end of this century.

However, the first entirely electronic local exchange in Australia opened at Endeavour Hills, a suburb of Melbourne, in 1981. This was the first of what will eventually be many so-called AXE exchanges, which were designed by L. M. Ericsson of Sweden.

In an AXE exchange, all control functions are carried out by specialised computers working under the instruction of complicated programs. There are a number of benefits to such full computerisation of the exchange functions. Firstly, the equipment is based on the extensive use of tiny electronic components and integrated circuits. These are on printed circuit boards which are easy to install, repair or replace, so reducing maintenance costs. Secondly, this miniaturisation of components has allowed substantial reduction in the size of exchanges at the same time as their capacity has been increased. Thirdly, many new customer facilities can be made available. These include the automatic re-routing of calls, abbreviated dialling, do-not-disturb facilities, and many others. Some of these extended facilities are also provided by ARE-11 exchanges. Fourthly, the introduction of AXE exchanges will simplify the administration of the network and allow its more efficient utilisation as well as modernising the charging and billing system for telephone accounts.

The Endeavour Hills exchange incorporates a reed-relay crosspoint switching system, but it has been decided that all AXE exchanges other than this first one will incorporate entirely digital switching methods in their group selector stages.

Digital switching is a radical new concept in telecommunications switching, and it relies entirely on the extremely high speed and logical power of modern computers and electronics. In a digital switching system there is no continuous electrical connection existing between the telephones of the two people speaking, as there is in both step-by-step and crossbar switching.

Instead, during a call passing through a digital switching exchange, the lines of the two subscribers are linked for only very brief periods of time, many thousands of times a second.

To explain how this works, it will be useful to look first at an increasingly common kind of telephone transmission called time division multiplexing using pulse code modulation. This sounds horrendous, but it is not all that hard to understand! The meaning of these terms is described much more fully in Telecom Information Kit No. 1, "Dots to Data". For our purposes here it will suffice to say that in this method of transmission, the human voice (or other sound to be transmitted) is sampled 8000 times a second and the level of the signal at the instant of sampling is transmitted as a binary number in a series of on-or-off pulses. This is called digital transmission, because the information representing the sound is sent as a number – a series of digits – rather than as a continuously varying electrical signal as in traditional telephone transmission.

7 The computer comes to the exchange

Telecom Australia

This conversion into digital form would normally occur at an exchange for transmission between exchanges, as the subscriber's lines will continue to use traditional methods for many years to come.

Because of the rapid operating speed of modern electronics, a typical digital transmission system can mix together thirty such telephone calls by taking a sample from each subscriber's line in turn, transmitting them one after the other, and returning to the first call by the time 1/8000th of a second has elapsed.

Now, such is the fantastically high speed of modern computers, that a specialised computer at the digital exchange can accept information from many such incoming digital channels, sort out where each voice sample needs to go, set up a connection path for a brief instant, send on the sample to the right outgoing channel, then go on to deal with the next sample.

When a caller dials his or her wanted number, a computer at the exchange works out what series of internal operations will be necessary to send a sample from the caller's line to the called subscriber's line, and it stores appropriate numbers representing this in one or more control stores or memories, along with control information for hundreds of other calls. When a sample comes in from this particular caller's line, it is kept in a kind of queue called a speech store. But instead of the normal kind of queue where the first person in is the first out, the samples are read out of the speech store, once it is full, in quite a different order than they came in, depending on the information in the control store.

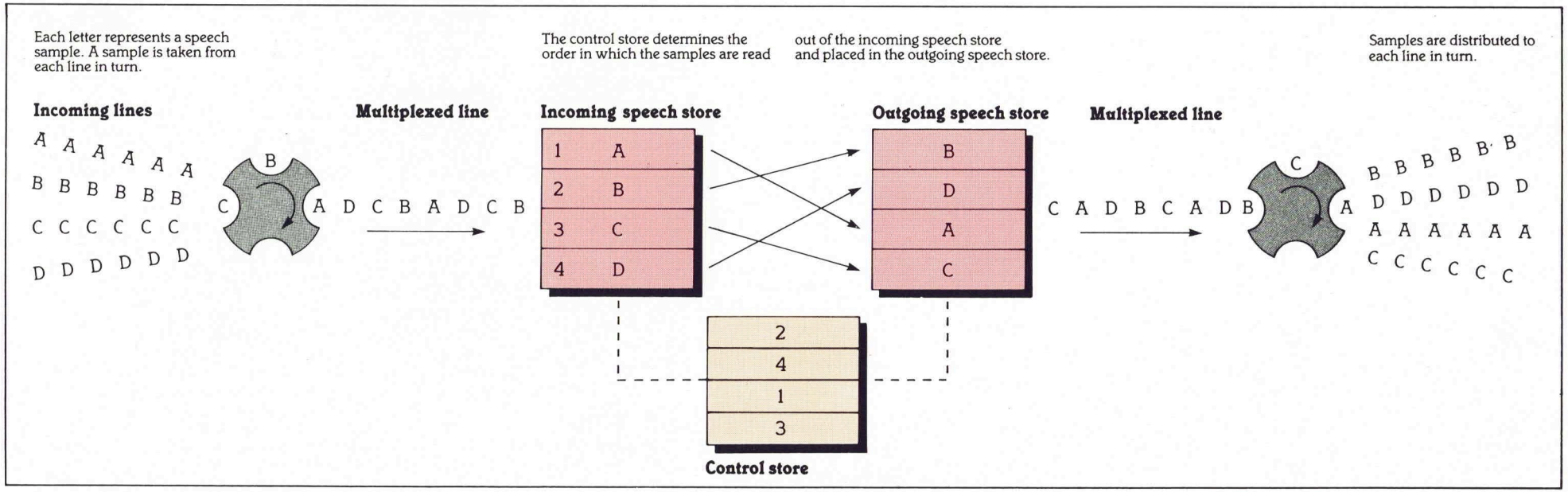
This re-ordering of the samples represents a switching process in time, rather than in space (see diagram). For an exchange handling a large number of lines, there will be a number of such time switches, or a combination of time switches and space switches (an internal computer version of the reed relay crosspoint switch).

Recall that the voice samples are just numbers to the computer. It can store them in its memory, switch them about and manipulate them just as it can when doing ordinary arithmetic.

Once one sample has been read from the incoming speech store and allowed to pass through any internal space switch to be stored in an outgoing speech store, a sample from another line is similarly transmitted through the exchange. After 512 such samples have been transmitted, the computer comes back to the first line again. Yet so fast is it that samples are taken and switched from a particular line 8000 times a second, and the users have no idea that their conversation is being carried on in such a piecemeal fashion!

All of this is a very far cry from the first simple switchboards operated by pushing plugs in and out of sockets, and the increase in efficiency is staggering.

This diagram represents the operation of a time switch in a digital exchange in an extremely simplified form. In a real situation, the samples are just numbers stored in electronic memories. Many multiplexed lines, each mixing together speech samples from 30 voice channels, are fed into the speech store, which is much larger in capacity than that shown here.


Each letter represents a speech sample. A sample is taken from each line in turn.
The control store determines the order in which the samples are read out of the incoming speech store and placed in the outgoing speech store.
Samples are distributed to each line in turn.
Incoming lines
A A A A A A
B B B B B B
C C C C C C
D D D D D D
Multiplexed line
A D C B A D C B
Incoming speech store
1 A
2 B
3 C
4 D
Outgoing speech store
B
D
A
C
Multiplexed line
C A D B C A D B
B B B B B B
D D D D D D
A A A A A A
C C C C C C
2
4
1
3
Control store

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THE SWITCHING PLACE

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